Spatio-temporal patterns of land use and cropping frequency in a tropical catchment of South India

F. Wilken[a,b], P.D. Wagner[c,b,*], B. Narasimhan[d,b], P. Fiener[a,b]

[a] Institut für Geographie, Universität Augsburg, D-86159 Augsburg, Germany
[b] Indo-German Centre of Sustainability, Indian Institute of Technology Madras, Chennai 600 036, India
[c] Department of Hydrology and Water Resources Management, Institute for Natural Resource Conservation, Kiel University, D-24118 Kiel, Germany
[d] Environment and Water Resource Engineering Division, Department of Civil Engineering, Indian Institute of Technology Madras, Chennai 600 036, India

A R T I C L E I N F O

Keywords:
Land use
Cropping frequency
Irrigation
Tropics
South India

A B S T R A C T

India's rapid population and economic growth leads to fast changing land use and management practices that have a major impact on the environment. Therefore, this study assesses spatio-temporal dynamics of land use and cropping frequencies using moderate resolution spaceborne data (Landsat 7 and LISS III). Based on a hierarchical knowledge-based classification approach, multi-temporal satellite data from the years 2000/2001 and 2010/2011 have been used to derive land use and cropping frequency maps. The approach adopted in this study resulted in a satisfactory classification quality as indicated by overall accuracies > 90% for the individual classifications. A reduced land use pressure on mountainous areas was found, indicated by an increasing development of forests within the transition zones between cultivated land and steep slopes. Furthermore, an increase of tree plantations points to a shift from drought vulnerable plants to less risk prone perennial plants. We found a higher cropping frequency in 2010/11 related to both inter-annual precipitation differences over the course of the rainy season and long-term socio-economic changes. While low yield areas are left for natural succession or switched to tree plantations, the cultivation of high yield areas was intensified.

1. Introduction

Land use is one of the most important human impacts on global and regional water cycles (Foley et al., 2005). The importance of land use changes for water resources management is widely recognized (DeFries & Eshleman, 2004; Stonestrom, Scanlon, & Zhang, 2009) and is illustrated by the fact that irrigated agriculture accounts for about 90 percent of water withdrawal in the developing world (Cai & Rosegrant, 2002). To account for future food demands, adaption of water management (e.g. irrigation efficiency) and land management (e.g. changes of cropland intensity) are required (Malek & Verburg, 2017).

Countries with rapidly growing economies and population often face dynamic changes in land use and cropping intensity (Rao & Pant, 2001). However, the patterns of land use intensity in these countries are often poorly understood (Kuemmerle et al., 2013). India, as a prominent example, experiences both rapid urban expansion (e.g., Wagner, Kumar, & Schneider, 2013) and increasing vulnerability of smallholder farmers with regard to climate change and climate variability (Jain, Mondal, DeFries, Small, & Galford, 2013; Morton, 2007).

Moreover, India is confronted with a very pronounced, monsoon-driven rainfall that results in seasonal water scarcity, so that water management is one of India's environmental major issues (Cosgrove & Cosgrove, 2012; Seckler, Barker, & Amarasinghe, 1999). Further, an increasing food and the associated irrigation water demand will exacerbate the current situation in the future (De Fraiture et al., 2007). Therefore, adapted land management strategies need to be developed and evaluated. Such strategies typically aim at reducing the agricultural water consumption (e.g., by changing to less water intensive crops, or by increasing water use efficiency) or sustaining and enhancing the use of rainwater harvesting structures. The evaluation of these measures substantially relies on accurate information of current and past land use and management. Remote sensing provides suitable data to derive spatially explicit land use information (Coops & Waring, 2001) that can serve as input data for e.g. hydrologic models (DeFries & Eshleman, 2004). However, the derivation of the spatio-temporal patterns of land use and cropping frequency in India is complex due to the variability of rainfall, e.g. land use patterns depend on the spatial distribution of hydrologic variables (Wagner & Waske, 2016) and multiple cropping depends on the available irrigation water (Jain et al., 2013). Moreover, arable land is highly fragmented due to the

* Corresponding author. Department of Hydrology and Water Resources Management, Institute for Natural Resource Conservation, Kiel University, Olshausenstr. 75, D-24118 Kiel, Germany.

E-mail address: pwagner@hydrology.uni-kiel.de (P.D. Wagner).

smallholder based agro-economic structures (Heller et al., 2012; Jain et al., 2013). Remote sensing based land use change investigations in South India are often based on a visual interpretation of satellite images (e.g., Chauhan & Nayak, 2005; Dharumarajan et al., 2017; Fox et al., 2017; Jaiswal, Saxena, & Mukherjee, 1999; Jayakumar & Arockiasamy, 2003; Muthukumar, 2013) and single-date classification schemes (e.g., Adhikari, Southworth, & Nagendra, 2015; Shamsudheen, Dasog, & Tejaswini, 2005; Shetty, Nandagiri, Thokchom, & Rajesh, 2005). Moreover, a majority of studies focused on shifts between urban and forest land use (e.g., Rahman, Aggarwal, Netzband, & Fazal, 2011; Venkatesh, Lakshman, & Purandara, 2014), whereas detailed information especially on changes in cropping frequency are still rare.

Against this background, the objectives of this study are: (i) To map land use and cropping frequencies and (ii) to analyse the spatio-temporal patterns of land use and cropping frequencies over a decade in the meso-scale catchment of the Upper Pennaiyar in South India.

2. Materials and methods

2.1. Study area

The Upper Pennaiyar catchment (5335 km^2, Fig. 1) is located in the Indian states of Tamil Nadu, Karnataka, and (to a small extent) Andhra Pradesh (Fig. 1). The elevation ranges from 1470 m in the northwest to 400 m above m.s.l. in the south where the Krishnagiri reservoir is located. The topography of the north-western (upper) parts is slightly undulated. Further downstream, a linear mountain range separates the upper part of the catchment from the lower part. The mountain range is mainly characterized by exposed bedrock and steep slopes. In the lower parts, the relief is relatively flat but occasionally interrupted by isolated rock outcrops.

The climate is tropical, dominated by the seasonality of the southwest and northeast trade winds (summer and winter monsoon, respectively; Fiener, Gottfried, Sommer, & Steger, 2014) with rainfall occurring between June and December. In the pre-monsoon season (March–May) regularly occurring thunderstorms cause rainfall events (Bhowmik, Roy, & Kundu, 2008). Due to the influence of both monsoon and the pre-monsoon, two annual precipitation peaks can be found, in May as a result of the pre-monsoon and in September/October caused by the summer/winter monsoon. The annual precipitation at Bangalore (at the western border of the catchment) and Krishnagiri (at the southeastern outlet of the catchment) are in the same range (Krishnagiri annual mean: 924 mm, standard deviation: 270 mm, daily maximum: 170 mm; Bangalore annual mean: 1074 mm, standard deviation: 283 mm, daily maximum: 306 mm for the period from 1982 to 2011). Due to the low latitude, the annual temperature amplitude is rather low (21 °C–28°; based on mean monthly temperatures measured at Bangalore between 1982 and 2011).

Arable cropping is traditionally carried out in two periods that are associated with water availability. During the rainy season (June to December), the so called *Kharif* crops (Krishna & Morrison, 2010) are cultivated based on a combination of rain-fed and irrigated farming. Typical *Kharif* crops are finger millet, groundnut and pulses; whereas rice is planted as a cash crop in areas of substantial irrigation potential. Following the *Kharif* crops, the so called *Rabi* crops are cultivated (January to March). Crop types in the *Rabi* season are strongly dependent on the local availability of irrigation resources and typically have a high water use efficiency, e.g. drought resistant finger millet can either be cultivated rain fed or irrigated. Cultivation during the summer period is negligible (Indian Ministry of Agriculture, 2013) and solely possible along perennial streams. In general, the cropping frequency is strongly linked to water availability and hence, the highest land management intensities are found in proximity to water harvesting ponds, perennial streams and in areas of shallow groundwater resources (Krishna, 2010). Whereas cropland is mostly located in relatively flat terrain that is suitable for irrigation, semi-natural forest as well as shrubland and grassland are mainly found at steeper slopes. In the west, the megacity Bangalore is expanding into the catchment area (Fig. 1). For the evaluation of spatially distributed changes, the catchment was sub-divided into 26 sub-catchments.

2.2. Data

Overall, six cloud-free scenes of the Landsat 7 Enhanced Thematic Mapper (ETM+; 30 m × 30 m) sensor were analysed for the cultivation period of 2000/01. As the swath of an individual ETM+ scene does not cover the entire study area, two corresponding scenes for each time step are merged. Hence, three scenes for the western and three scenes for the eastern part of the catchment were used. For 2010/11 we used three cloud-free Resourcesat-1 Linear Imaging Self-scanning Sensor (LISS; 23.5 m × 23.5 m) III scenes (Indian Space Research Organization) that cover the entire catchment (Table 1). The sensors were chosen with respect to their similar spatial and spectral resolution. The spatial resolution of the LISS III was linearly resampled to match the resolution of the ETM+ sensor (30 m × 30 m). Scenes at the end of *Kharif* and during *Rabi* were selected, as cloud-free images were not available for the peak monsoon season. To derive the maximum extent of the pond surface area, representing the case of a very wet monsoon season, an additional scene from the Landsat 5 Thematic Mapper (TM) in the exceptionally wet year of 1992 was used. Pre-processing of the satellite data includes an atmospheric correction based on the Fast Line-of-sight Atmospheric Analysis of Spectral Hypercubes (FLAASH; Adler-Golden et al., 1999; Matthew et al., 2000, 2002) and a geometric correction based on measured reference points for those scenes that exhibit geometric errors larger than the size of one pixel. For topographical information, the 90 m × 90 m resolution digital elevation model of the Shuttle Radar Topography Mission (SRTM; Jarvis, Reuter, Nelson, & Guevara, 2008) was used and linearly resampled to match the ETM+ sensor resolution of 30 m × 30 m.

Three field surveys (Dec. 2011; Mar. 2012; May 2012) were conducted at ten test sites in the catchment area to map forest, shrub- and grassland, rocks, urban areas, ponds, tree plantations, palm trees, rice and other cropland. These areas were complemented with additional ground truth interpreted from Google Earth images (DigitalGlobe, CNES, Astrium; version 7.1.2.2041), summing up to a total area of approximately 1190 ha. For the cultivation period of 2000/01 ground truth was interpreted from those Google Earth images that were temporarily as close as possible to 2000/01. In addition, these data were checked for consistency with the satellite data to ensure that land use did not change. The ground truth data was split into two independent data sets, one used for training the classification algorithm and the other used for validating the classification results.

2.3. Land use and cropping frequency classification

The analysis of temporal changes in land use and in particular in cropping frequency (expressed as the number of crops cultivated per year) requires the use of multi-temporal satellite images which allow a regular intra-annual monitoring of land use and enable a comparison of different cultivation periods (Heller et al., 2012). Linking multi-temporal satellite images to additional sources of geo-information (e.g., digital elevation model (DEM), plant growth conditions) enhances the level of information, enables implementation of knowledge-based rules, and has demonstrated its abilities to improve land use and management analysis (e.g., Benediktsson & Sveinsson, 2003; Watanachaturaporn, Arora, & Varshney, 2008).

The classification is based on a stepwise determination of different land use and cropping frequencies within arable land. Therefore, we combined knowledge-based rules and geo-information (e.g. slope, irrigation potential) with single-date and multi-temporal satellite data. Overall, the following classes were distinguished: Forest, shrub- and grassland, rock, urban, ponds (with current water extent), tree

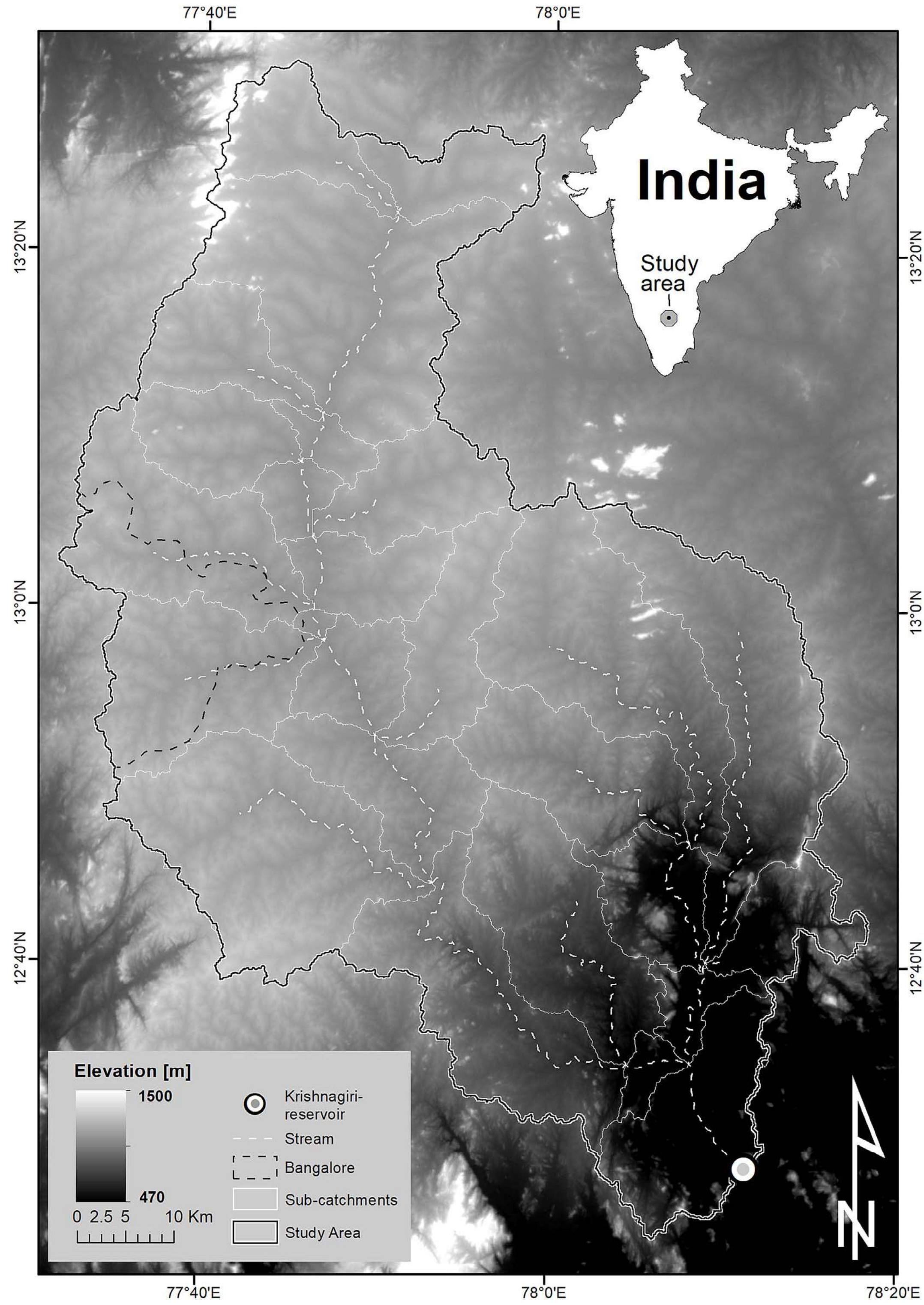

Fig. 1. Location and topography of the Upper Pennaiyar river catchment.

Table 1
Satellite scenes used in this study; TM is thematic mapper on Landsat 5, ETM+ is enhanced thematic mapper on Landsat 7, LISS-III is multi-spectral sensor on Resourcesat-1.

TM West	ETM+ West	ETM+ East	LISS-III
Jan. 14th, 1992	Nov. 27th, 2000	Dec. 6th, 2000	Nov. 21st, 2011
	Jan. 14th, 2001	Mai 12th, 2000	Feb. 6th, 2011
	Mar. 3rd, 2001	Feb. 24th, 2001	Mar. 2nd, 2011

plantation, palm tree, rice, single and multiple cropped cropland. We used a hierarchical knowledge-based classification approach that incorporates threshold values for areas not suitable for agriculture (slope > 8%) and suitable for irrigation agriculture (< 8 m height above surface water derived from the stream network and the DEM, Fiener et al., 2014) and a maximum likelihood classifier. To remove potentially misclassified spatially singular pixels, a majority filter was applied on a moving 3 × 3 raster window.

Date-specific classes like ponds, cropland as well as less complex

Table 2
Validation matrix based on independent ground truth data derived from field surveys and the analysis of Google Earth scenes, given as producer's and user's accuracy, respectively (P.-Acc. = Producer's Accuracy, U. Acc. = User's Accuracy).

Class	2000/01 Landsat 7 (ETM+)		2011 IRS-P6	
	P.-Acc. [%]	U.-Acc. [%]	P.-Acc. [%]	U.-Acc. [%]
Filled Pond	98.9	99.8	86.1	100.0
Pond	98.8	98.5	100.0	74.9
Urban	87.7	100.0	89.2	99.9
Arable	98.7	76.0	97.1	81.3
Palm Tree	92.3	91.7	84.5	98.0
Tree Plantation	75.8	99.8	84.7	98.0
Forest	96.7	95.3	97.7	96.3
Shrub or Grassl.	90.0	90.4	81.2	80.8
Rock Outcrops	82.6	87.4	76.5	80.6
Overall Accuracy [%]	91.7		90.8	

classes like shrubland and grassland, rock outcrops and forest areas are based on single-date classifications, whereas palm tree, tree plantations, and urban areas were classified with multi-temporal data (Table 1). Due to spectral similarities of rice and palm trees, we used a threshold of 0.5 for the normalized difference vegetation index (NDVI) to separate these classes. The NDVI threshold had to be exceeded in all three scenes for a classification of palm trees. Rice fields were already harvested in the late *Kharif* scenes so that the threshold would not be exceeded in at least one scene. Similarly, plant vitality in the *Rabi* season was used to derive the cropping frequency within the cropland class: It can be assumed that nearly all fields are cropped during *Kharif* season when water availability is sufficient (Jain et al., 2013). Consequently, high plant vitality (NDVI > 0.5) during *Rabi* season indicates multiple cropped fields, whereas low plant vitality (NDVI ≤ 0.5) indicates single cropped fields. To prevent a potential weather induced bias, we used the first *Rabi* scene (6 Feb.) for this differentiation in 2011, as 40 mm precipitation in late February influenced plant vitality in the second *Rabi* scene (2 Mar.).

Landsat ETM+ and IRS P6 LISS III were used to derive the two land use classifications for 2000/01 and 2010/11, respectively. Differences between the two points in time are derived by a post-classification assessment. These differences in land use and cropping frequencies are analysed on the catchment and sub-catchment scale.

3. Results

3.1. Land use classifications

The hierarchical knowledge-based classification approach provided land use maps for 2000/01 and 2010/11 with good overall accuracies above 90% (Table 2). The individual classes were reliable with producer's accuracy and user's accuracy well above 75% (Table 2). Fig. 2 shows the two land use classifications. Tree plantations are dominantly located in the undulated upper (northern) part of the catchment. Forests can rather be found in the steep and remote areas, whereas shrub- and grassland is often located in the transition zones between mountainous regions and arable land. The catchment is dominated by arable land use. The cropping frequency is higher in the valley bottoms near water sources. Similarly, multiple cropped rice and palm trees are cultivated near the stream network or downstream of ponds, particularly in the lower (southern) part of the catchment.

3.2. Spatio-temporal patterns of land use and cropping frequencies

On the catchment scale, the changes in the land use distribution are generally small (Fig. 3). The most pronounced alterations are: (i) a decrease of shrub and grassland from 4.7% in 2000/01 to 3.7% in 2010/11 (251 km^2–196 km^2) and an increase of forest areas (2000/01: 3.3%, 176 km^2; 2010/11: 4.4%, 233 km^2), (ii) an increase of tree plantations from 6.2% in 2000/01 to 8.7% in 2010/11 (332 km^2–463 km^2), (iii) a decrease of palm tree areas from 1.4% in 2000/01 to 0.7% in 2010/11 (73 km^2–38 km^2), and (iv) an increase of urban areas mainly associated with the expansion of Bangalore city

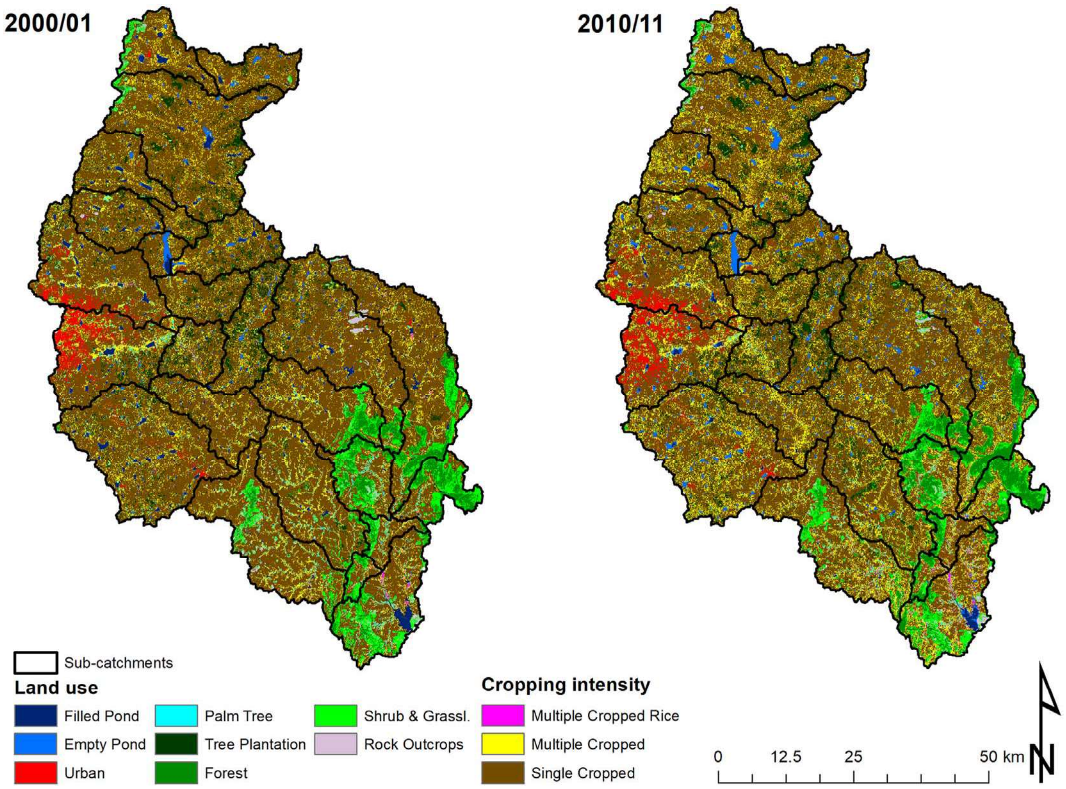

Fig. 2. Land use classifications of 2000/01 and 2010/11.

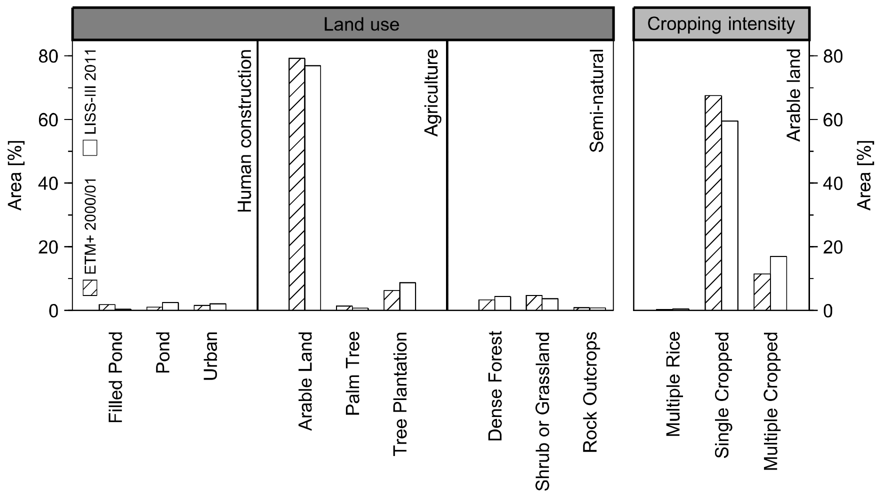

Fig. 3. Area of the different land use and cropping intensity classes for the two time slices (2000/01 and 2010/11) as derived from the land use and cropping frequency classification.

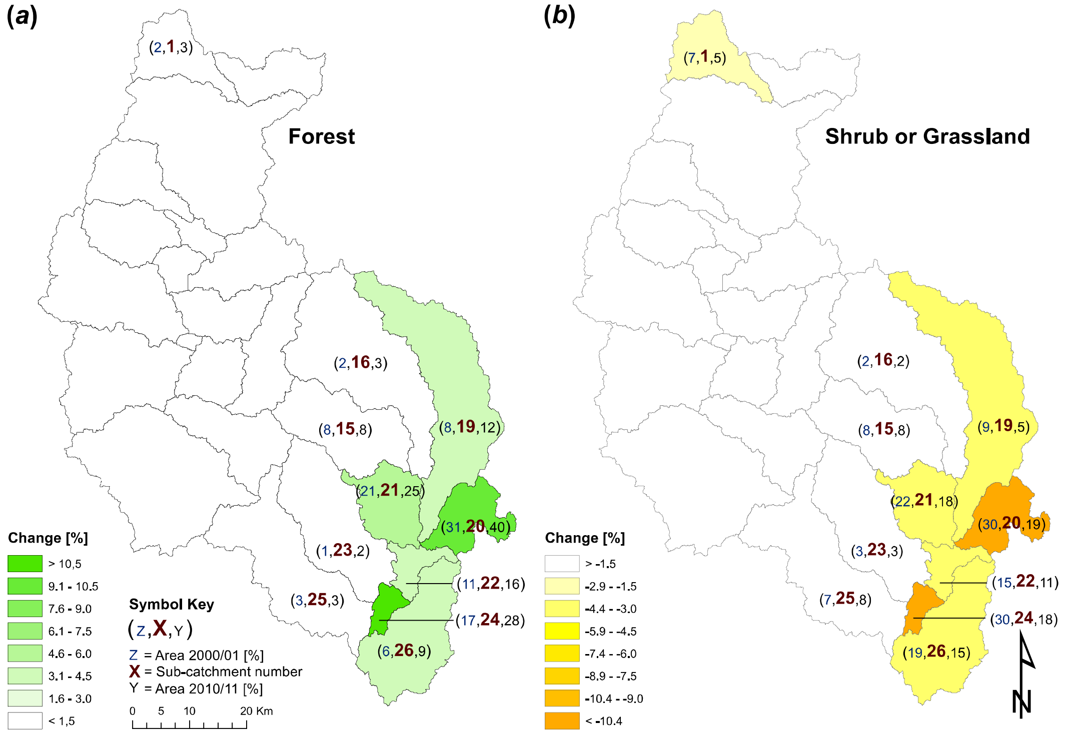

Fig. 4. Sub-catchment wise change in percent catchment area for the class of dense forest (*a*) and the shrub or grassland class (*b*) from 2000/01 to 2010/11.

from 1.6% in 2000/01 to 2.1% in 2010/11 (83 km^2–111 km^2).

Arable land shows a minor decrease of 2.3% of the catchment area from 2000/01 to 2010/11. Within the arable land class, cropping frequencies changed as follows: Single cropping decreased from 67.5% to 59.5% (3600 km^2–3176 km^2) and multiple cropping increased from 11.4% to 16.9% (610 km^2–903 km^2). Multiple cropped rice, cultivated during both *Kharif* and *Rabi* season, slightly increased (from 0.26%, 14 km^2 to 0.43%, 23 km^2).

The maximum extent of the ponded area of 2.8% (Fig. 3) was not fully covered by water in the late *Kharif* scenes. Only 1.8% and 0.4% water area were detected for 2000/01 and 2010/11 (94 km^2 and 20 km^2), respectively (Fig. 3).

On the sub-catchment scale, changes in land use and cropping frequency were much more pronounced. The most prominent land use changes in the different areas of the catchment were:

(i) Within all sub-catchments that contain considerable mountainous areas (19–22, 24, 26) dense forest strongly increased (Fig. 4a). The maximum increase (11.7% of the sub-catchment area) was found in sub-catchment 24, which almost doubled its forest area. Sub-catchment 20 was covered by more than 30% of dense forest already in 2000/01, thus the increase of 10% of the sub-catchment area is not as extreme as in sub-catchment 24. The change mainly resulted from a shift from shrub- and grassland to forest (92% of all pixels additionally classified as forest in 2010/11 were classified as shrub and grassland in 2000/01). Moreover, the sub-catchment map that shows the loss of shrub- and grassland (Fig. 4b) corresponds well with the map that shows the gain of forest on the sub-catchment scale (Fig. 4a).

(ii) Tree plantations increased in most sub-catchments, particularly

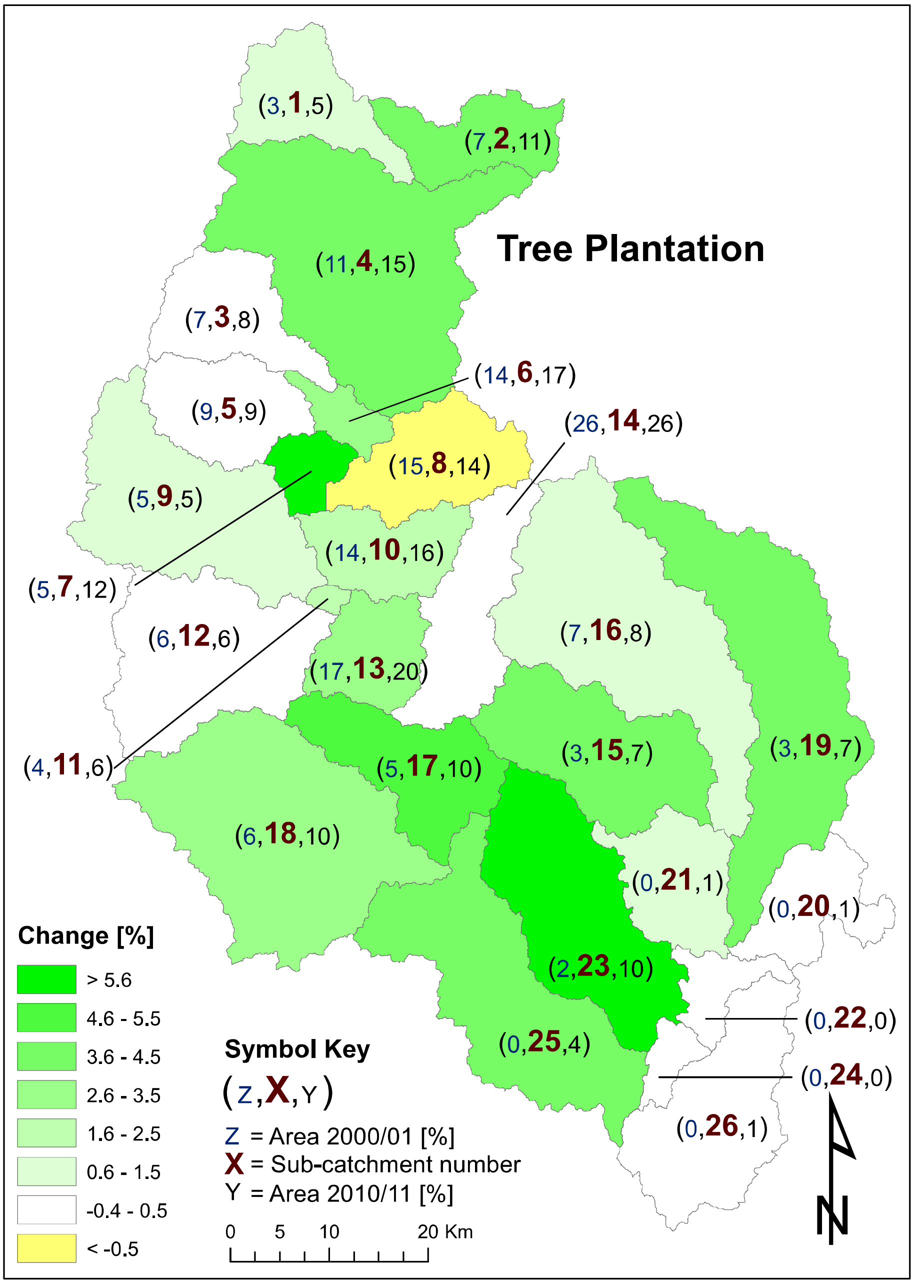

Fig. 5. Sub-catchment wise change in percent catchment area for tree plantations from 2000/01 to 2010/11.

north of the Krishnagiri plain (sub-catchments 15, 23, 25; Fig. 4). For example in sub-catchment 23, the tree plantation area increased from 2.4% to 9.6%. As mango is an important tree plantation, our result agrees with a considerable increase of mango in all districts as indicated by the Indian land use statistics (Indian Ministry of Agriculture, 2013). (iii) Cropping frequency increased in all catchments. Multiple cropped fields increased in all sub-catchments between 0.1% and 9.2% of the sub-catchment area, whereas single cropped fields decreased between 1.8% and 14.4% of the sub-catchment area in all but one sub-catchment (minor increase of 0.6% in sub-catchment 14; Fig. 6). The increase of cropping frequency was less pronounced in the sub-catchments that include the city of Bangalore (Bangalore Urban district) (9, 12) and in the sub-catchments in the central eastern part (8, 14–16; Fig. 6). Most pronounced increases (> 7% of the sub-catchment area) were found in the south-western parts (18, 20, 25, 26), in the centre (7,10), and in the northern parts (3) of the catchment.

4. Discussion

Our results show an increase of forest within the mountain ranges and a potential decline of land use pressure on forests. Traditionally, Indian tropical dry forests and shrublands were used for collecting fire wood and feeding the livestock of subsistence farmers (Hedge & Enters, 2000; Schmerbeck & Hiremath, 2007; Schmerbeck & Knoke, 2003). To keep these areas accessible, it is a wide spread management technique to regularly burn the underbrush (Schmerbeck & Fiener, 2015; Schmerbeck & Seeland, 2007). In consequence, forest and shrubland never develop to a dense canopy. Nevertheless, the MODIS burned area product (Roy, Boschetti, Justice, & Ju, 2008) shows large inter-annual variations for the fire frequency (Fig. 7), but does not draw a clear trend for the investigated period from 2000/01 to 2010/11. In a case study of a mountainous area in the Palni Hills of Tamil Nadu, an extreme reduction of fuel wood harvesting was identified from 65 t km^{-2} yr^{-1} in 1991 to 16 t km^{-2} yr^{-1} in 2012 (Schmerbeck, Pouyet, & Patnaik, 2012). In

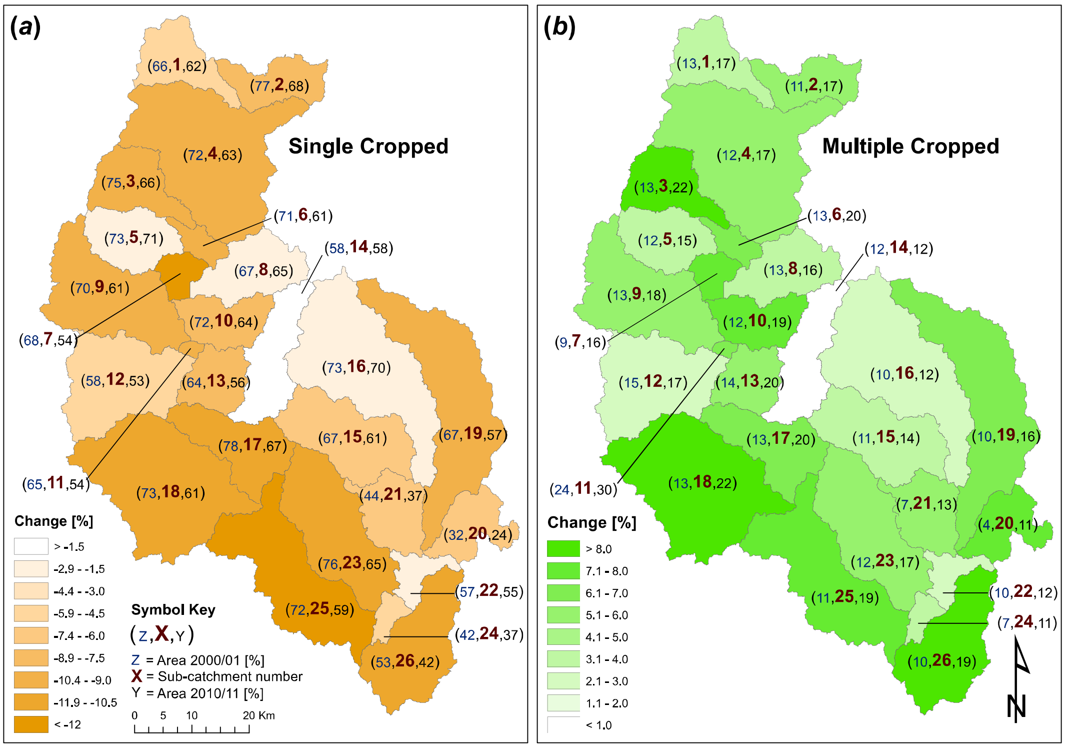

Fig. 6. Sub-catchment wise change in percent catchment area for the single cropped (***a***) and multiple cropped (***b***) classes from 2000/01 to 2010/11.

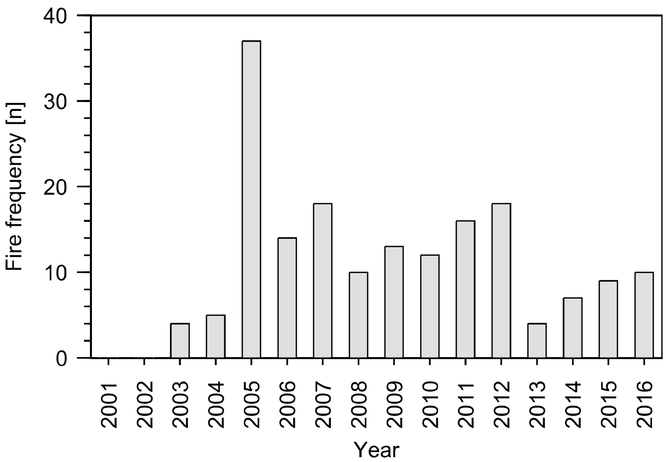

Fig. 7. MODIS based annual fire frequency (Roy et al., 2008) in the Nilgiri mountains and the central mountain range of the Upper Pennaiyar catchment.

contrast, livestock grazing remained almost constant within the period. Hence, land use pressure on the forest substantially decreased even under growing population. While livestock grazing was typically observed at the easier accessible border regions, fuel wood was collected in the remote central forest areas (Schmerbeck et al., 2012). This spatial pattern is reflected in the classification, as in 2000/01 forest cover was mainly found in the remote central regions of the mountain ranges, while these areas expanded and became less patchy in 2010/11. Adhikari et al. (2015) carried out a remote sensing based land cover classification in a small area (~500 km^2) in direct proximity to the western border of the Upper Pennaiyar catchment. They also found an increase in forest area that mainly resulted from a densification in the central forest areas. Within the study of Schmerbeck et al. (2012), new income options that are more attractive than low profit and high effort fuel wood harvesting were detected as the main driver of a reduction in forest use. Therefore, land use pressure on forests seems to be related to economic development.

Tree plantations increased in almost all sub-catchments but particularly at the border between the flat and water-rich lower regions and the slightly undulated and rather water scarce terrain (sub-catchments 23, 25, Figs. 5 and 1). Presumably, this region is dominated by marginal land of insufficient economical yield. A widespread trend of increasing fallow land in South India was reported by Dharumarajan et al. (2017). This change mainly takes place at low yield agricultural regions (Natarajan et al., 2010). Due to a lower drought vulnerability and thus lower dependency on precipitation events, the risk of a bad harvest is lower for perennial plants (Zollinger, Kjelgren, Cemy-Koenig, Kopp, & Koenig, 2006). This change might be on the one hand an adaptation strategy to large meteorological variability of the study area and on the other hand a result of a socio-economic development that goes along with reduced forest use intensity. Agricultural wages have increased all over India (Reddy, Reddy, & Bantilan, 2014), which can be attributed to a growing economy and the Mahatma Gandhi National Rural Employment Guarantee Act that guarantees hundred days of employment per year for each adult living in a rural area. Tree plantations are less labour intensive and are therefore one possibility for the farmers to cope with rising wages. Again, the results of Adhikari et al. (2015) are in great agreement with our findings, showing that the area covered by tree plantations doubled from 1992 to 2007. Further support is given by the land use statistics of the Indian Ministry of Agriculture (2013) that also reflect a pronounced increase of mango tree plantations. However, the detected change might be slightly overestimated as the producer's accuracy for tree plantation is lower in the classification of 2000/01 (75.8%, Table 2) compared to 2010/11 (84.7%, Table 2).

Throughout the catchment, our results show that cropping frequency was lower in 2000/01 compared to 2010/11. The areas of both multiple cropped cropland and multiple cropped rice were larger in 2010/11 as compared to 2000/01. An intensification of agricultural practices in the region seems reasonable due to a growing food demand (Biradar & Xiao, 2011). However, besides socio-economic drivers, the cropping frequency is highly sensitive to irrigation water availability (Jain et al., 2013). Therefore, the cropping frequency changes between

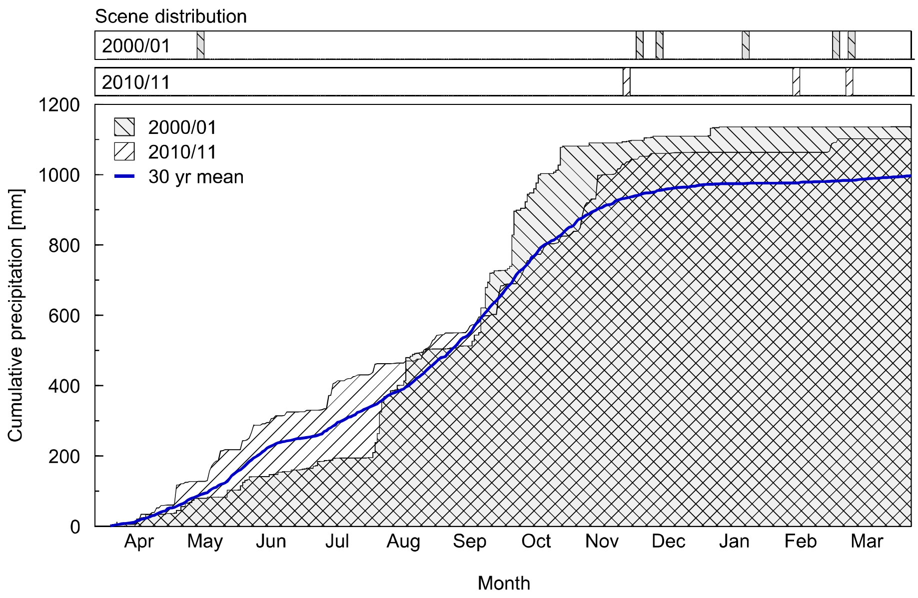

Fig. 8. Temporal distribution of used satellite scenes (bars at the top) in relation to precipitation distribution. The mean of the Bangalore and Krishnagiri stations was used for the cultivation period 2000/01 and 2010/11. Furthermore, the 30 year average precipitation distribution is shown.

2000/01 and 2010/11, partly result from an inter-annual variability of water availability. This variability is discernible for extreme years like 2002/03 (annual precipitation sum: 709 mm) and 2006/07 (annual precipitation sum: 793 mm), when the El-Nino related weakening of the monsoon caused a massive reduction of cultivated areas in the catchment (approx. 10% less arable land use in Kolar district; Indian Ministry of Agriculture, 2013). Although the precipitation sums in both investigated time periods were similar, the precipitation distribution showed major differences over the course of 2000/01 and 2010/11 (Fig. 8). In 2000/01, 75% (2010/11: 35%) of the monsoon precipitation occurred between August and October, whereas in 2010/11 the monsoon started earlier and provided regular precipitation from April to December. It can be hypothesized that the stretched and evenly distributed precipitation period in 2010/11 allowed for higher cropping frequencies. Surprisingly, the observed filled pond area was smaller in 2010/11 (0.4% of the catchment area as compared to 1.8% in 2000/01), which usually is an indicator for irrigation water scarcity. A possible explanation might be an enhanced infiltration that is related to a stretched precipitation period. Moreover, management decisions as well as decreased maintenance of ponds (Anbumozhi, Matsumoto, & Yamaji, 2001; Palanisami & Meinzen-Dick, 2001) may have led to lower water levels and an associated decrease in water-filled area. Due to ongoing agricultural mechanization and affordable groundwater pumping, the use of groundwater steadily increased whereas pond irrigation steadily declined (Amarasinghe, Singh, Sakthivadivel, & Palanisami, 2009; Palanisami & Meinzen-Dick, 2001; Siderius et al., 2015). Moreover, groundwater use enables irrigation in locations where farmers do not have regular access to surface water provided from the ponds. Hence, the amount of surface water does not necessarily represent the available amount of irrigation water. In summary, the differences in cropping frequency between 2000/01 and 2010/11 are driven by both, intra-annual differences in environmental conditions as well as long-term socio-economic changes.

The assessment of land use information in South India using (moderate resolution) satellite images faces a number of challenges that derive from environment specific characteristics: (i) Traditional subsistence farming (farms are mostly smaller 1 ha; FAO, 2005; Manjunatha, Anik, Speelman, & Nuppenau, 2013) and flood irrigation have contributed to a very patchy agricultural landscape. These smallholder farms are often surrounded by trees (e.g., palm trees). Using moderate resolution satellite data, small fields result in a large number of pixels with mixed spectral signatures. This complicates successful classification, as already mentioned in other studies in South India (e.g., Heller et al., 2012; Shanmugam, Ahn, & Sanjeevi, 2006). (ii) Depending on the strength of monsoon, the proximity to perennial streams and water harvesting structures (mostly small ponds), up to three crops per year can be cultivated in the region (Krishna, 2010). Hence, multiple satellite images are needed of which the satellite acquisition date is of critical importance. However, the need for cloud-free satellite data often constrains the number of suitable satellite scenes for such an assessment. ESA's Sentinel mission with its open access and free of charge SAR data (Aschbacher & Milagro-Pérez, 2012) might provide a good additional and cloud cover independent source of information for the detection of cropping frequencies. (iii) Inter and intra-annual variability of monsoonal rainfall mainly defines water availability and has a strong impact on the dynamics of cropping frequencies. It is therefore challenging to find comparable periods of rainfall to derive long-term changes in cropping frequency.

5. Conclusion

Between 2000/01 and 2010/11 substantial spatially distributed changes and variations of land use and cropping frequency were found within the sub-catchments of the Upper Pennaiyar catchment. We found an increase of forest areas in all mountainous regions that contradicts the general assumption of an increasing land use pressure on forests due to population growth (urban area 2000/01: 83 km^2, 2010/11: 111 km^2). In agreement with that, is a substantial shift from cash crops to less maintenance demanding tree plantations, which was detected in the undulated (northern) parts of the catchment. On arable land, an increase of multiple cropped fields points to an intensified agricultural use in 2010/11. Moreover, arable land use in the study area is largely controlled by the strength and intra-annual distribution of the monsoon precipitation, which should therefore be taken into account for land management analysis.

Acknowledgements

We gratefully acknowledge financial support from the Indo-German Centre for Sustainability (IGCS) funded by the German Academic Exchange Service (DAAD) on behalf of the German Federal Ministry of Education and Research (BMBF), and the Indian Institute of Technology Madras. We sincerely thank Karl Schneider, University of Cologne, and Björn Waske, Freie Universität Berlin, for their valuable inputs and support of this study. The assistance during field work by Theresa Warnk, Jayakumar Renganathan, and Liji Vinod is gratefully acknowledged. Special thanks also go to the numerous farmers who welcomed us with great hospitality.

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